SPECTRALLY INVISIBLE FRAMING OF HIGH ERROR

RATE DATA SIGNALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[01]   This is the first application filed for the present invention.

MICROFICHE APPENDIX

[02]   Not Applicable.

TECHNICAL FIELD

[03]   The present invention relates to high error rate data communications, and in particular to a method and system for spectrally invisible framing of high error rate data signals.

BACKGROUND OF THE INVENTION

[04]   In the modern communications network space, signal reach and spectral density are important factors in overall network cost.   Assuming other factors to be equal, increases in either signal reach or spectral density tend to reduce overall network cost and are thus very attractive to network service providers.

[05]   Signal reach is the distance that an optical signal can be transmitted through a fiber, before conversion to electronic form is required to perform signal regeneration. Using suitable optical amplifiers and optical processing techniques, between 10 and 20 fiber spans (of 40-80 km each) can be traversed by an optical signal before optical/electrical conversion and regeneration are required.

[06]   Spectral density, which is normally expressed in terms of bits/sec/Hz (b/s/Hz), is a measure of the extent to which the theoretical maximum bandwidth capacity of an optical channel is utilized. This value is generally determined by dividing the line rate (in bits/sec.) of a channel by the optical frequency (in Hz) of that channel. A spectral density of 1 indicates that, for a given channel, the line rate and optical frequency are equal. Existing telecommunications systems commonly operate at line rates of approximately 2.5Gb/s to 40Gb/s. At a line rate of 10Gb/s, current Wavelength Division Multiplexed (WDM) (or Dense Wave Division Multiplexed (DWDM)) transmission systems achieve a spectral density of approximately 0.1 b/s/Hz. If the line rate is increased to 40Gb/s, the spectral density increases to approximately 0.4b/s/Hz, illustrating the advantages of increasing the line rate.

[07]   However, increasing the line rate raises a number of difficulties.   In particular, at line rates of about 10Gb/s and higher, the optical characteristics of a fiber link have an increasingly important effect on the signal-to-noise ratio at the receiving end of the link, which manifests itself as an increased bit error rate of the regenerated signal.   In addition, the physical limitations of electronic circuits at each end of the link mean that signal processing becomes progressively less reliable as the line rate increases. Both of these difficulties become of particular importance at line rates of 40Gb/s, and present significant obstacles to further increases in line rate beyond this speed.

[08]   One known method of addressing the problem of increased bit error rates at higher line rates is to encode

the data signal using a known Forward Error Correction encoding scheme (e.g. BCH) prior to transmitting the signal through the link. The FEC-encoded signal can be decoded at the receiving end of the link, to recover the original data signal. FEC encoding enables errored bits within the recovered data signal to be corrected at the receiving end of the link, and thereby enables effective data transport in spite of the increased bit error rates encountered at high line rates.

[09]   Difficulties resulting from the physical limitations of electronic circuits can be addressed by dividing the signal into a plurality of parallel sub-streams, which can be parallel processed at a lower line rate (e.g. 2.5Gb/s). The sub-streams can be independently FEC encoded, and interleaved (e.g. using a conventional sequential interleaving process) into a single high-speed signal having a line rate exceeding that which can be accommodated with conventional electronic signal processing hardware. However, the success of this approach is entirely dependent on the ability of the node at the receiving end of the link to successfully separate the signal to recover each of the sub-streams at the receiving end of the link. This, in turn, requires a framer capable of correctly identifying each frame of each sub-stream within the high-speed signal, which is at least partially dependent on the bit error rate of the high-speed signal. For example, within the Synchronous Optical Network (SONET) protocol, a framer can typically tolerate a bit error rate of less than about 0.01 without declaring a loss-of-frame condition.

[10]   However, as mentioned previously, the bit error rate of a received signal tends to increase with higher

line rates. The need to keep bit error rates lower than about 0.01 imposes a significant limitation, which frequently requires a designer to trade off signal reach in order to attain higher line rate (spectral density).

[11]   One way of improving the operation of framer is to insert a predetermined unique synchronization word into each sub-stream prior to interleaving the sub-streams into the signal. The framer can then identify each of the sub-streams by searching the signal to detect each of the unique synchronization words. However, this arrangement suffers limitations in that correct detection of the unique synchronization word is affected by the bit error rate, and thus degrades as the bit error rate increases. Additionally, because the unique synchronization word is inserted into each sub-stream at regular periods (typically at each frame), the energy spectrum of the signal becomes characterized by a recurring bit pattern having a fixed frequency. This is detected within both optical and electronic signal processing devices as an harmonic signal component, which tends to degrade the efficiency of these signal processing devices.

[12]   Accordingly, a method and apparatus for reliably framing high bit error rate signals composed of multiple interleaved sub-streams, while maximizing the efficiency of signal processing equipment, remains highly desirable.

SUMMARY OF THE INVENTION

[13]   An object of the present invention is to provide a method and apparatus for reliably framing a high bit error rate data signal composed of multiple interleaved sub-streams.

[14]   Another object of the present invention is to provide a method and apparatus for reliably framing a data signal using a spectrally invisible synchronization word.

[15]   Accordingly, an aspect of the present invention provides a method of framing a data signal received through a link of a communications network, the data signal comprising M (an integer, M>1) interleaved sub-streams. In accordance with the method of the invention, the data signal is inverse multiplexed to generate M recovered sub-streams. The recovered sub-streams are then processed, in parallel, to detect a respective unique synchronizing word in each of the recovered sub-streams within a predetermined search window.

[16]   Another aspect of the present invention provides a synchronizing word adapted for uniquely identifying a respective one of M (an integer, M>1) sub-streams interleaved within a data signal. The synchronizing word includes a non-unique position word and a non-unique identifier word. The position word has a significant hamming distance relative to a shifted version of itself. The identifier word is selected from a set of predetermined identifier words, and has a significant hamming distance relative to each of the other identifier words in the set.

[17]   A further aspect of the invention provides a framer adapted for framing a high error rate data signal received through a link of a communications network, the data signal comprising M (an integer, M>1) interleaved sub-streams, the framer comprising means for detecting a respective unique synchronizing word in each one of M recovered sub-streams extracted from the data signal, within a predetermined search window.

[18]   Another aspect of the invention provides a method of transporting a data signal comprising a plurality of interleaved sub-streams through a link of a communications network, each sub-stream being uniquely identified by a respective synchronization word inserted into the respective sub-stream prior to interleaving the sub-streams into the data signal, wherein a bit pattern of each synchronizing word is selected such that an energy spectrum of the synchronization words interleaved within the data signal is substantially white.

[19]   The width of the predetermined search window may be determined using an expected delay between corresponding data units of a first interleaved sub-stream and a last interleaved sub-stream of the data signal. In some embodiments, the search window corresponds to a portion of the data signal received during a period of up to twice an expected delay between corresponding data units of a first interleaved sub-stream and a last interleaved sub-stream of the data signal

[20]   Detection of a unique synchronizing word within each sub-stream may be accomplished by independently searching each recovered sub-stream to detect a respective synchronizing word. When a synchronizing word is detected in a sub-stream, a respective individual frame found state is asserted for a first predetermined period of time. A master frame found state can then be asserted if the individual frame found state is asserted in respect of all of the sub-streams within the predetermined search window.

[21]   The first predetermined period of time may be determined using an expected delay between corresponding

data units of a first interleaved sub-stream and a last interleaved sub-stream of the data signal.

[22]   In some embodiments, each recovered sub-stream is searched by buffering a portion of the recovered sub-stream. The buffered sub-stream data can then be compared against each one of a set of predetermined unique synchronizing words, to detect a respective one of the set of predetermined unique synchronizing words in the recovered sub-stream.

[23]   In some embodiments, each synchronizing word comprises a non-unique position word and a non-unique identifier word. In such cases, comparison of buffered sub-stream data against each one of a set of predetermined unique synchronizing words may be accomplished by comparing the buffered sub-stream data against each one of a set of predetermined valid position words to detect a position word in the recovered sub-stream. When a position word is detected in the recovered sub-stream, the buffered sub-stream data can be compared against each one of a set of predetermined valid identifier words to detect an identifier word in the recovered sub-stream.

[24]   In some embodiments, an individual frame found state may be asserted by de-asserting an individual Out-of-Frame flag associated with the respective recovered sub-stream. Information indicative of the synchronizing word detected in the respective recovered sub-stream may also be asserted. This information may be used identify a respective one of the interleaved sub-streams, and associating the identified interleaved sub-stream with the recovered sub-stream. In some embodiments, the search of the recovered sub-stream can be reinitialized if the

identified interleaved sub-stream has previously been associated with another one of the recovered sub-streams.

[25]   In some embodiments, assertion of the master frame found state can be accomplished by monitoring a number of recovered sub-streams for which respective individual frame found states are simultaneously asserted. A location in the data signal at which individual frame found states are simultaneously asserted in respect of at least N (an integer 1<N<M) of the M recovered sub-streams can then be detected.   The search window can then be asserted bracketing the detected location at which individual frame found states are simultaneously asserted in respect of at least N of the recovered sub-streams.   Finally, the master frame found state is asserted if individual frame found states are asserted in respect of all of the recovered sub-streams within the asserted search window.

[26]   The value of N may be determined using an expected probability of an individual frame-found state being incorrectly asserted in respect of any one of the M recovered sub-streams. In some embodiments, N is 4.

[27]   It is possible that, following assertion of the predetermined search window, an individual frame-found state will not have been asserted in respect of at least one recovered sub-stream.   In such cases, the search of the affected recovered sub-stream can be narrowed to the portion of the recovered sub-stream within the asserted search window. Framing of the data signal may be restarted if the master frame found state is not asserted within a second predetermined period of time.   This second predetermined period of time may be defined as a predetermined number of frames following a first assertion

of the search window. The number of frames may be determined using an expected probability of the frame-possible state being incorrectly asserted, and may, for example, be about ten.

[28]   In some embodiments, a bit pattern of the synchronizing word is selected such that an energy spectrum of respective synchronization words of each of the sub-streams interleaved within the data signal is substantially white.

[29]   In some embodiments, respective lengths of the position and identifier words are selected using one or more of: a probability of incorrectly detecting the synchronizing word in the data signal; and a mean time to correctly declare the master frame found state. The respective hamming distances of the position and identification words may be selected using an expected bit error rate (BER) of the data signal. The expected BER may be about 0.05, or less. For example, the position word may have a length of at least 16 bits, and at most 32 bits, and a hamming distance of about 10 relative to a shifted version of itself. The identification word may have a length of about 10 bits and a hamming distance of about 5 relative to the other identification words in the set.

BRIEF DESCRIPTION OF THE DRAWINGS

[30]   Further features and advantages of the present invention will become apparent from the following detailed description, taken in combination with the appended drawings, in which:

[31]   FIG. 1. is a block diagram schematically illustrating operation of a framer in accordance with an embodiment of the present invention;

[32]   FIG. 2 is a block diagram schematically illustrating elements of a master framer and an individual framer of the framer of FIG. 1;

[33]   FIGs. 3a and 3b show a state diagram schematically illustrating state transitions of the IF state machine of each individual framer of FIG. 1; and

[34]   FIG. 4 is a state diagram schematically illustrating state transitions of the MF state machine of the master framer of FIG. 1.

[35]   It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[36]   The present invention provides a robust system for framing high error rate data signals composed of multiple interleaved sub-streams. FIG. 1 is a block diagram schematically illustrating principle elements in a system in accordance with the present invention. As shown in FIG. 1, the system comprises a sub-stream processor 2 which operates to insert a predetermined unique synchronization word 4 into each sub-stream 6 in a transmitting node 8 of a communications network. The processed sub-streams 10 are then multiplexed by a multiplexer 11 into a single high-speed data signal 12 prior to electrical/optical conversion for transmission through a link 14 of the communications network to a receiving node 16. At the receiving node 16, the high-speed data signal 12 is

optical/electrical converted and de-multiplexed, by a demultiplexer 18 which operates to reverse the multiplexing operation of the multiplexer 11, and thereby generate recovered sub-streams 20 corresponding to respective ones of the processed sub-streams 10.

[37]   In the illustrated embodiment, the optical link 14 is illustrated as a single span between the transmitting and receiving nodes 8, 16. However, it will be appreciated that the optical link 14 may include multiple spans, and traverse one or more network devices (e.g. optical amplifiers) intermediate the transmitting and receiving nodes 8,16. The transmitting and receiving nodes 8,16 may be any network nodes in which optical signals are converted into electrical signals and regenerated for processing. Exemplary network nodes of this type include add-drop-multiplexers (ADMs), routers, and cross-connects.

[38]   In order to maximize both the line rate and signal reach within the optical fiber link 14, the signal to noise ratio of the data signal 12 received at the receiving node 16 will tend to be comparatively low. This low signal to noise ratio will be evidenced by a comparatively high bit error rate within the received data signal 12, and this bit error rate will also be reflected in each of the recovered sub-streams 20 extracted from the received data signal 12. It is anticipated that short-term bit error rates of 0.01, with bit error rates of as high as 0.05, may be encountered within each of the recovered sub-streams 20 during system start-up. Additionally, in practical implementations, it is impossible to guarantee that a sub-stream 10 output by the signal processor 2 through a given channel "A" will be output by the demultiplexer 18 through a corresponding channel "A". In general, the

channel through which a recovered sub-stream 20 is output
from the demultiplexer 18 at the receiving node 16 will be
different from the channel through which the original
sub-stream 10 was output by the signal processor 2 at the
transmitting node 8. Thus, the present invention provides
a robust framer 22 which is adapted to reliably achieve
frame lock in respect of each of the recovered
sub-streams 20 (even at high bit error rates), and which
associates each output channel of the demultiplexer 18 with
a respective one of the original processed sub-streams 10
in order to facilitate any necessary channel re-ordering
downstream of the framer 22(not shown). These objectives
are accomplished by the functionality of the framer 22, in
combination with the format of the synchronizing words 4
inserted into each sub-stream 6 prior to interleaving the
processed sub-streams 10 into the data signal 12. An
exemplary format of synchronization words 4 in accordance
with the present invention is shown below in Table 1.

Table 1

	Synchronization Word (4)	
	Position Word (24)	Identifier Word (26)
	length = 22 bits	length = 10 bits
Sub-Stream	Hamming Distance = 10	Hamming Distance = 5
1	0000010000111010110111	0000000000
2	1111101111000101001000	0000011111
3	0000010000111010110111	0011100011
4	1111101111000101001000	0011111100
5	1111101111000101001000	1111011011
6	1111101111000101001000	1111000100
7	1111101111000101001000	1100111000
8	0000010000111010110111	1100100111
9	0000010000111010110111	1111000100
10	0000010000111010110111	1111011011

Sub-Stream	Synchronization Word (4)	
	Position Word (24)	Identifier Word (26)
	length = 22 bits	length = 10 bits
	Hamming Distance = 10	Hamming Distance = 5
11	1111101111000101001000	1100100111
12	0000010000111010110111	0011111100
13	0000010000111010110111	0000011111
14	0000010000111010110111	1100111000
15	1111101111000101001000	0011100011
16	1111101111000101001000	0000000000

[39]   In the embodiment of Table 1, each synchronization word 4 is a 32-bit sequence composed of: a position word 24 used to indicate a frame phase (nominally the beginning of each frame) of a respective sub-stream 10; and an identifier word 26 used, in combination with the position word 24, to uniquely identify each sub-stream 10 within the data signal 12. In addition, the bit sequence of each synchronization word 4 (that is, the position word 24 and the identifier word 26 taken together) is selected such that the energy spectrum of the interleaved synchronization words 4 within the data signal 12 is substantially white. This renders the interleaved synchronization words 4 spectrally invisible to optical devices within the link 12, thereby enabling optimization of the link performance.

[40]   As shown in Table 1, the position word 24 and identifier word 26 each have a respective length and hamming distance. In each case, the respective length and hamming distance are selected to enable robust frame detection and bit error tolerance. In particular, the length of the position word 24 is selected to enable the framer 22 to accurately identify the position word 24 within a recovered sub-stream 20, and a significant hamming

distance is used to provide bit error tolerance. In this respect, a "significant" hamming distance refers to a hamming distance that is at least ½ of the maximum theoretically possible hamming distance, based on the length of the respective word.

[41]   In the illustrated example, the position word 24 has a length of 22 bits, and a hamming distance of ten relative to a shifted version of itself. Using the framing algorithm described below with respect to FIGS. 2 through 4, a 22-bit position word length yields a high probability of correctly finding the position word 24 within a recovered sub-stream 20. A hamming distance of ten relative to a shifted version of itself, means that ten errored bits must occur within a sequence of 22 bits of a recovered sub-stream 20 in order for the position word 24 to be confused with a shifted version of itself. This implies a high probability of correctly identifying the phase of the position word 24 (and thus achieving frame lock), even within a high error rate sub-stream. As may be appreciated, increasing the hamming distance tends to increase error tolerance, but at a cost of increased demand on system resources, and possibly longer times to correctly acquire frame lock. A position word 24 having a length of 22-bits and a hamming distance of ten relative to a shifted version of itself represents a compromise between error tolerance and frame acquisition time.

[42]   It will be noted that a large number of possible unique position words 24 exist having a length of 22-bits and a hamming distance of 10 relative to a shifted version of itself. In the embodiment illustrated in Table 1, two unique position words 24 are used repeatedly, which reduces hardware and/or software requirements within the framer 22

(as will be described below) while being sufficient for an
embodiment of the invention in which 16 sub-streams 10 are
interleaved into the data signal 12.   It will be
appreciated however, that more than two unique position
words 24 may be used.   For example, each sub-stream 10 may
be assigned a unique position word 24, if desired.

[43]   As mentioned previously, the identifier word 26 is
used in combination with the position word 24 to uniquely
identify each sub-stream 10 within the data signal 12. Thus
it is convenient to define a set of predetermined
identifier words 26, each of which can be used in
combination with each one of the unique position words 24.
In the embodiment illustrated in Table 1, a set of eight
unique identifier words 26 is defined.   Each of these
identifier words 26 is used in combination with each one of
the two unique position words 24 to yield 16 unique
synchronization words 4 that uniquely identify each one
of 16 sub-streams 10. As shown in Table 1, each identifier
word 26 has a length of 10 bits and a hamming distance of
five relative to each of the other identifier words in the
set.

[44]   As with the position word 24, the length of the
identifier word 26 is selected to ensure accurate detection
of the identifier word 26 within a recovered sub-stream 20
(following detection of the position word 24), while the
hamming distance provides bit error tolerance.

[45]   In   combination,   the 22-bit   position   word 24
and 10-bit   identifier   word 26   yield   robust   framing
operation, with steady state bit error rates of 0.01, and
an ability to acquire and maintain frame for bit error
rates of up to 0.05, with acceptable reliability.

[46]   As is known in the art, modern optical networks
utilize automatic optimization of elements in a link.
During start-up and optimization of the link, control
parameters are typically perturbed to find the optimum
operating point. Until steady state operation is achieved
during start-up, the link may have BERs far exceeding those
acceptable for normal operation. Loss of frame during this
period prevents the system from optimizing operation, or
may prevent recovery from some unusual perturbation. While
the data at BER=0.01 is useless, if frame lock is
maintained, the system can perform its optimization
sequence, resulting in a much lower operating BER. Using
the synchronizing word 4 described above, the framer of the
present invention will maintain frame lock, with reasonable
probability, during excursions to BER=0.05.

[47]   As shown in FIG. 1, the framer 22 has a
hierarchical architecture comprising a respective
individual framer 28 for framing each of the recovered
sub-streams 20, and a master framer 30 for controlling
operations of each individual framer 28 and for
establishing a frame lock condition with respect to the
data signal 12 as a whole.

[48]   FIG. 2 is a block diagram schematically
illustrating principle elements of each individual
framer 28 and the master framer 30, as well as principle
messages exchanged between each individual framer 28 and
the master framer 30 during frame acquisition in accordance
with an embodiment of the present invention. Exemplary
operations of the individual framer 28 and the master
framer 30 are illustrated in FIGs. 3a and 4 respectively.

[49]   As shown in FIG. 2, each individual framer 28 generally comprises a buffer 32 such as a first-in-first-out (FIFO) for receiving and buffering a respective recovered sub-stream 20 output by the demultiplexer 18 (see FIG. 1); a position comparator 34 for comparing the buffered sub-stream data to each of the known position words 24; a symbol comparator 36 for comparing the buffered sub-stream data to each of the known identifier words 26; and an individual framer state machine 38 for controlling operations of the individual framer 28. Each of the elements of an individual framer 28 may be implemented by any suitable combination of hardware and/or software, in accordance with the requirements of each specific implementation. As shown in FIG. 2, exemplary outputs generated by each individual framer 28 include an Out-Of-Frame flag (OOF(i)) 40; a Found_Position_Word 42; and a Found_Symbol 44, each of which are forwarded to the master framer 30. The OOF(i) 40 may conveniently be provided as a binary signal generated by the position comparator 34, based on the results of comparison of the buffered sub-stream data with the known position words 24. For example, the position comparator 34 may assert OOF(i) 40 (that is, output a binary "1") when the buffered sub-stream data does not match any known position word 24, and therefore the individual framer 28 is in an "out of frame" condition. When the position comparator 34 determines that the buffered sub-stream data does match one of the known position words 24, the position comparator 34 can de-assert OOF(i) 40 (that is, output a binary "0") indicating that the individual framer 28 has located a frame within the recovered sub-stream 20. Simultaneously, the position comparator 34 may also output the Found_Position_Word 42 to indicate which one of the known

position words 24 has been found within the buffered
sub-stream data. The Found_Position_Word 42 may take any
convenient value such as, for example, the position word
itself, or a predetermined tag value which can be used by
the master framer 30 to identify the position word found by
the individual framer 28. Similarly, the symbol
comparator 36 may output the Found-Symbol 44 based on the
results of comparison between the buffered sub-stream data
and the known identifier words 26. When one of the known
identifier words 26 is located within the buffered
sub-stream data, the identity of the identifier word is
forwarded to the master framer as the Found-Symbol 42.
This may take the form of the identifier word 26 located by
the symbol comparator within the buffered sub-stream data,
or a predetermined tag value that may be used by the master
framer 30 to identify the specific one of the known
identifier words found by the individual framer 28.

[50]   As shown in Fig. 2, the master framer 30 generally
comprises a master framer state machine 46; and a
registry 48 for enabling the master framer 30 to associate
each of the individual framers 28 with a respective one of
the processed sub-streams 10 originally multiplexed into
the data signal 12 at the transmitting node 8. As shown in
FIG. 2, the master framer 30 receives the OOF(i) 40,
Found_Position_Word 42, and Found-Symbol 44 generated by
each of the individual framers 28. In addition the master
framer 30 generates a search window signal 50 and a
Four_Found signal 52, both of which are propagated
simultaneously to all of the individual framers 28. The
master framer 30 also generates a respective Flush
signal 54 for each individual framer 28, so that the master
framer 30 can cause a flush (i.e. a reset) of a selected
one of the individual framers 28.

[51] Principle operations of each of the individual framers 28 and the master framer 30 are described below in greater detail with reference to FIGs. 3a, 3b and 4.

[52] FIGs. 3a and 3b show a state diagram schematically illustrating state transitions of the individual framer state machine 38 within each individual framer 28. As shown in FIG. 3a, upon start-up or reset of the framer 22, or upon reception of a Flush signal 54 from the master framer 30, the IF state machine 38 enters a State-0 100 in which the OOF(i) 40 is asserted (e.g. set to "1") to indicate an out-of-frame condition, and other internal variables and registers of the IF state machine 38 (e.g. a Frame-bucket) are initialized in a conventional manner 102. The IF state machine 38 then enters a State-1 104 in which the position comparator 34 operates to compare buffered sub-stream data with each of the known position words 24 (at 106). If a match is found, the OOF(i) 40 is de-asserted (to indicate that a position word 24 has been found within the respective sub-stream) for a predetermined period of time (at 108). The duration of this predetermined period of time is preferably selected based on an expected time interval between a bit of a first interleaved sub-stream 10a and a corresponding bit of a last interleaved sub-stream 10n within the high-speed data signal 12. This means that, in the event that each individual framer 28 correctly identifies a respective position word 24 within its respective recovered sub-stream 20, then corresponding OOF(i) signals 40 will be de-asserted by each of the involved individual framers 28 simultaneously, for at least a portion of the predetermined period. In the embodiment illustrated in FIGs. 1 through 4, the high-speed data signal 12 corresponds to an OC-768 signal composed of sixteen interleaved OC-48

sub-streams. In this situation, corresponding bits of a first interleaved sub-stream 10a and a last interleaved sub-stream 10n will be separated within the high-speed data signal 12 by up to 250 nano-seconds (nSec) (for the case of parallel optical transmission of the sixteen OC-48 sub-streams 10). Thus, for the illustrated embodiment, the duration of the predetermined period of time, during which OOF(i) 40 is de-asserted by the individual framer 28, can be set to 250 nSec. Simultaneously with de-assertion of the OOF(i) 40 (at 108), the individual framer 28 also asserts the Found_Position_Word signal 42, as described above with reference to FIG. 2.

[53]   As may be expected, the probability of finding any given position word 24 within a frame of a recovered sub-stream 20 depends, at least in part, on the size of each frame. In the illustrated embodiment, each frame of a recovered sub-stream is of STS-48 size, and the resulting probability of finding a given 22-bit position word 24 at one or more locations within that frame is too high to enable reliable framing of the sub-stream 20. However, the probability of simultaneously finding respective different 22-bit position words 24 within two or more of the recovered sub-streams 20 decreases rapidly as the number of involved sub-streams 20 increases. Thus, as will be described in greater detail below with reference to FIG. 4, the master framer 30 monitors the OOF(i) 40 asserted by each of the individual framers 28. If, at any instant, at least four of the individual framers 28 simultaneously de-assert OOF(i) 40, then the master framer 30 determines that at least four of the individual framers 28 have simultaneously located position words within their respective recovered sub-streams, and asserts the Four_Found signal 52. Otherwise, the master framer 30

de-asserts the Four_Found signal 52. As shown in FIG. 3a, each individual framer 28 monitors the Four_Found signal 52 asserted by the master framer 30 (at 110). If the Four_Found signal 52 is not detected (at 110), then OOF(i) 40 is asserted (at 112) and the individual framer 28 continues comparing buffered sub-stream data with the known position words 24 as described above. If the Four_Found signal 52 is detected (at 110), and if (at 114) the OOF(i) 40 has also been de-asserted, the IF state machine 38 proceeds to State-3 116 (FIG. 3b). Otherwise, if (at 114) the OOF(i) 40 has been asserted, then the IF state machine 38 proceeds to State-2 118.

[54]   Within State-2 118, the individual framer 28 continues searching for a position word 24 within its respective buffered sub-stream data. However, within this state, the search is restricted to a search window corresponding to a portion of the recovered sub-stream 20 bracketing the location at which position words 24 have been found by other ones of the individual framers 28. As with the predetermined period of time in which the OOF(i) 40 is asserted (at 108), the duration of the search window may be determined on the basis of the anticipated delay between a bit of a first interleaved sub-stream 10a and a corresponding bit of a last interleaved sub-stream 10n within the high-speed data signal 12. Thus for example, in the illustrated embodiment, the search window may be set to encompass that portion of the respective recovered sub-stream 20 commencing 250 nSec prior to assertion of the Four_Found signal 52, and ending 250 nSec after assertion of the Four_Found signal 52. The timing of the search window is determined by the master framer 30 (e.g. based on the timing of the Four_Found signal 52) and communicated to the individual

framer 28 by means of the Frame_Interval signal 50 (see FIG. 2). For example, within the search window, the master framer 30 may assert the Frame_Interval signal 50, and de-assert the Search window signal 50 otherwise.

[55]   Within State-2 118, the IF state machine 38 uses the Frame_Iinterval signal 50 to control operations of the position comparator 34. Thus, when the Frame_Interval signal 50 is asserted (at 120), the position comparator 34 operates as described above to compare the buffered sub-stream data to each of the known-position words 24 (at 122). If one of the known position words 24 is found within the buffered sub-stream data (at 122), the individual framer 28 (at 124) de-asserts OOF(i) 40 for the predetermined period of time (e.g. 250 nSec), the Found_Position_Word signal 42 is asserted to identify the position word 24 found in the buffered sub-stream data, and the IF state machine 38 proceeds to State-3 116.

[56]   As mentioned previously, the symbol comparator 36 operates to compare buffered sub-stream data to each one of the known identifier words 26. In principle this operation may proceed in parallel with operation of the position comparator 34, for example, by examining a portion of the buffered sub-stream data having a predetermined relationship with the buffered sub-stream data being examined by the position comparator 34. Thus, as shown in FIG. 3b, when the IF state machine 38 enters State-3 116, the symbol comparator 36 is checked (at 126) to determine if the buffered sub-stream data matches any of the known identifier words 26. If no match is found, the symbol comparator 36 continues examining the buffered sub-stream data within State-3. Otherwise, if a match is found between the buffered sub-stream data and one of the known

identifier words 26, the individual framer 28 asserts a value of the Found-Symbol signal 44 that is representative of the identifier word 26 found within the buffered sub-stream data (at 128). As mentioned previously, the value of the Found-Symbol signal 44 may be the actual identifier word 26 found by the symbol comparator 36, or a predetermined tag value (not shown) representative of the identifier word 26 found by the symbol comparator 36.

[57] As described above with reference to FIG. 2, the master framer 30 includes a registry 48 for associating each one of the individual framers 28 with a respective one of the processed sub-streams 10 originally multiplexed into the high-speed data signal 12. Thus an associated registry process of the master framer 30 uses the Found_Position_Word signal 42 and the Found-Symbol signal 44 asserted by the individual framer 28 to identify (at 130) the respective recovered sub-stream 20 being received by the individual framer 28. If the identified sub-stream 20 has already been associated with another one of the individual framers (at 132), as indicated by an appropriate entry in the registry 48, then the master framer 30 asserts a Flush signal 54 (at 134) to reset the individual framer 28 back to State-0 100, and thus re-start the process of acquiring and identifying the respective recovered sub-stream 20. Otherwise, the registry process updates the registry 48 (at 136) to associate the individual framer 28 with the identified sub-stream 20. One or more additional variables may also be set within the master framer 30 (at 138) to reflect association of the individual framer 28 with the identified sub-stream 20. In the illustrated embodiment, for example, the master framer 30 includes a "Taken" array (not shown)) having respective fields corresponding to each one of the

recovered sub-streams 20 of the high-speed data signal 12. Thus, as shown in FIG. 3, following association of an individual framer 28 with a respective identified sub-stream 20, the corresponding field of the "Taken" array is also updated for use by the master framer state machine 46 as will be described in greater detail below with reference to FIG. 4.

[58]   Upon successful completion of State-3 processing as described above, the individual framer state machine 38 enters State-4 (at 140), in which the respective recovered sub-stream 20 is monitored for loss of frame lock.   As shown in FIG. 3, this may be accomplished, in a bit error tolerant manner, by comparing buffered sub-stream data to the synchronization word 22 (i.e. the position word 24 + identifier word 26) found during State-1, State-2 and State-3 processing of the individual framer state machine 38, and then calculating a Frame_Bucket value (at 142) indicative of a proximity between the buffered sub-stream data and the identified synchronization word 22. This Frame_Bucket value is then compared (at 144) against a predetermined threshold.   Based on the results of this comparison, the IF state machine either remains in State-4 (at 146), or resets to State-0 (at 100) and begins the process of re-acquiring the respective recovered sub-stream 20.

[59]   FIG. 4 is a state diagram schematically illustrating state transitions of the MF state machine 46 of the master framer 30.   In general, the MF state machine 46 runs in parallel with the IF state machines 38 of the individual framers 28, and the MF state machine 46 traverses each of its own states as the IF state machines 38 traverse States-0 through 4 as described above.

Thus upon start-up or reset of the master framer 30, the MF
state machine 46 enters State A (at 150), and initializes
the registry 48 and other internal variables, as well as
each of the signals 50-54 asserted by the master framer 30
(at 152).   Following   initialization,   the   MF   state
machine 46 transitions to State B (at 154), and examines
the OOF(i) signals 40 being asserted by each of the
individual framers 28 in order to determine the number of
individual framers 28 that have identified one of the known
position   words   24   within   their   respective   recovered
sub-stream 20.   In the illustrated embodiment, this is
accomplished by summing the OOF(i) signals 40 (at 156), and
comparing the summation result to a predetermined threshold
(at 158).   Using this approach, a summation result of less
than a threshold value of 13 (in an embodiment in which
sixteen sub-streams are interleaved into the high-speed
data signal 12) indicates that at least four of the
individual   framers   28   are   simultaneously   de-asserting
OOF(i) 40, thereby indicating that one of the known
position words 24 has been found within their respective
recovered sub-stream 20. When this condition is satisfied,
the   Four_Found   signal 52   is   asserted   by   the   master
framer 30, and a timer (e.g. a frame counter) is
initialized to zero (at 160). The MF state machine 46 then
transitions to State C (at 162) in order to complete frame
acquisition.

[60]   Upon entry into State C (at 162), the MF state
machine 46 increments the timer (at 164), and determines
whether or not all of the individual framers 28 have been
associated with one of the sub-streams in the registry 48
(discussed above with reference to FIGs. 2 and 3a-3b).   In
the illustrated embodiment, this is accomplished by ANDing
the "Taken" array (at 165), and examining the result of the

ANDing operation (at 166). If the AND operation result is "0", then it is determined that at least one of the individual framers 28 has not been associated with a sub-stream 20 in the registry 48. Accordingly, the timer is compared with a predetermined threshold (at 168). If the timer is less than the predetermined threshold, the MF state machine 46 increments the timer (at 164) before re-evaluating whether or not all of the individual framers 28 have been associated with a respective sub-stream 20 (at 165 and 166). On the other hand, if the timer is equal to the predetermined threshold (in this case 10), the MF state machine 46 returns to State A (at 150), and resets the entire framer 22 to re-start the frame acquisition process. The purpose of the predetermined threshold, in this case, is to prevent a condition in which the master framer state machine 46 reaches State C on the basis of erroneous detection of position and identifier words 24,26 within four or more individual framers 28, but cannot complete State-C (and thereby achieve frame lock) because the remaining individual framers 28 are unable to locate position and identifier words 24,26 within the asserted search window. Thus, in the present embodiment, if all of the individual framers 28 are unable to identify respective position and identifier words 24,26 within their respective recovered sub-streams 20, within a predetermined number of frames (in this case, ten) after entering State-C (at 162) then the entire framer 22 is reset.

[61]   If it is determined (at 166) that all of the individual framers 28 have been associated with a respective one of the sub-streams 20 in the registry 48, then the MF state machine 46 declares a frame lock condition by de-asserting Master Out Of Frame (MOOF) (that

is, setting the MOOF value to binary "0") (at 170), and then transitions to State-D (at 172).

[62]   Processing of the MF state machine 46 within State-D (at 172) is analogous to the processing of each IF state machine 38 within State-4 (discussed above with reference to FIG. 3). Thus, the MF state machine 46 calculates (at 174) a Master_Bucket (MB) value indicative of the proximity of each of the synchronization words 22 with the buffered sub-stream data within each of the individual framers 28. The MB value is then compared (at 176) with a predetermined threshold which is selected to enable robust retention of the frame lock condition in a bit error tolerant manner, while at the same time enabling a reset of the framer 22 in an event that frame lock is lost. In the present case, if the calculated MB value is less than 1, then it is determined (at 176) that frame lock has been lost, and the MF state machine 46 resets the framer 22 and returns to State A (at 150). Otherwise, the MF state machine 46 continues monitoring the frame lock status of the framer 22 within State-D.

[63]   The embodiment(s) of the invention described above is(are) intended to be exemplary only. The scope of the invention is therefore intended to be limited solely by the scope of the appended claims.